On the Design and Validation of Surface Bidirectional Reflectance and Albedo Models

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Physically based mathematical models of the bidirectional reflectance of terrestrial surfaces are needed to compute the albedo of these surfaces. Such models are also necessary to interpret satellite remote sensing data in terms of the fundamental physical parameters of the soil and vegetation which control how radiation is reflected by these media. Since a wide variety of mathematical functions can be made to fit the observed reflectances, a clear and discriminating strategy must be thought out to validate the proposed models. Such a strategy consists in inverting the models against reflectance data, and comparing the retrieved values of the parameters to those obtained independently from field or laboratory measurements. In this article, we review the state-of-the-art in modeling the bidirectional reflectance of natural surfaces, describe how such models can be validated, and highlight the remaining challenges for the remote sensing community.

INTRODUCTION

Much of the literature on remote sensing in the optical spectral region is devoted to the analysis and interpretation of the spatial, temporal, and spectral variations of the reflectance of natural and artificial targets. These investigations have yielded important results, and the spectral signatures of a variety of typical surfaces have been documented, allowing the identification of ground targets. Most of the airborne and satellite observations have been taken at or close to nadir, looking down at the surface. This choice has consistently been made to minimize the effect of the optical thickness of the atmosphere, which can affect the signal in significant ways through absorption and scattering. Imaging instruments, however, necessarily take observations in a variety of directions (e.g., scan angle) across the flight path, and the small field of view of most instruments render all observations directional. Furthermore, since the Sun is always in a specific position with respect to the target, all reflectance measurements are intrinsically bidirectional.

It has long been recognized that the reflectance of natural surfaces such as soils and vegetation canopies is anisotropic, that is, that the reflectance (brightness) of the surface depends strongly on the position of the observer relative to the target. This feature of rough surfaces has been extensively exploited by space scientists to study the characteristics of planetary surfaces such as the Moon, but largely ignored as far as surfaces on Earth are concerned. In fact, many

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investigations of the reflectance of terrestrial targets assume these surfaces to be Lambertian, that is, to reflect light equally in all directions. Such an assumption greatly simplifies the analysis of the observations, but also severely limits the validity or applicability of the results.

Relatively few studies have dealt with this issue so far, but the importance of bidirectional effects is now widely recognized as a significant problem that needs immediate and focused attention. On the one hand, users of satellite remote sensing data would like to process their data in such a way that the signal they study is free from directional effects that are outside their concerns. On the other hand, recent theoretical investigations indicate that the anisotropy of the surface results from the internal structure of the scattering medium, and that information on the "compacity" of this medium is contained in, and can be retrieved from, directional variations in reflectance (e.g., Verstraete et al., 1990; Pinty et al., 1990). Modelers are therefore interested in investigating further the relation between structure and anisotropy, in order to derive additional information on the surface.

The current focus on global environmental and climatic change will only increase the demand for such an understanding. Indeed, the Earth Radiation Budget Experiment (ERBE), which has been measuring both the incoming and outgoing radiation fluxes at the top of the atmosphere, has documented the strong anisotropy of these fluxes, and suggested both surface and atmospheric contributions, including by clouds. It has also become clear that the anisotropy of a surface is scale-dependent, and is related to the ratio of a "roughness parameter," representative of the structural inhomogeneities of the scattering medium, over the linear size of the pixel viewed by the sensor (Hapke, 1984). Hence, over very large areas viewed by low resolution sensors, the anisotropy results mainly from the topography, whereas, for small areas viewed at higher resolution, the distance between the individual scatterers becomes the dominant factor.

It is now understood that much of the anisotropy fundamentally results from the shadowing of some scatterers by others, that is, from the structure of the medium. Two specific effects seem to contribute: First, the orientation distribution of the scatterers with respect to the geometry of illumination and observation seems to play an important role, particularly for nonuniformly distributed flat scatterers. In addition, the correlation between the transmission of radiation along the incoming and outgoing directions is responsible for the relatively large increase in backscattering known as the "hot spot" region. Attempts to include a mathematical description of this latter effect in radiation transfer models has often lead to the addition of an ad hoc parameter, whereas the latest theoretical studies have shown the hot spot reflectance peak to derive from a more universal treatment of radiation transfer is a scattering medium when the size and orientation of these scatters are taken into account (Pinty and Verstraete, 1991).

In this article, we propose a coherent strategy to develop and validate models of the bidirectional reflectance of natural surfaces. After discussing the needs for such models, we review the broad categories of models currently available and highlight the principal remaining challenges. In particular, we will argue that much more comprehensive data sets must be acquired and that more thought should be given to the selection and documentation of an optimization procedure that could be used for model inversion purposes.

RATIONALE FOR MODELING SURFACE ALBEDO AND REFLECTANCE

For all practical purposes, solar radiation is the only source of energy for the climate system. After interacting with the atmosphere (and being both partly absorbed and scattered by it), a fraction of this incoming solar radiation is absorbed at the surface. The remainder is reflected back to the atmosphere, and the ratio of this reflected energy to the incoming radiation, usually for a finite and relatively large spectral region, is called the albedo of that surface. It is this absorbed energy that controls most processes at the surface of the Earth, including the exchanges of heat, moisture, and carbon, as well as all biological activity.

Climate Models Requirements

The general concern about climatic and environmental degradation has highlighted the advantages of global climate models (e.g., Henderson-

Sellers and Blong, 1989; Schneider, 1989). These models allow the mathematical representation of the most important physical, chemical, and biological processes, and in particular of the fluxes of matter, energy and momentum over terrestrial surfaces (e.g., Verstraete and Dickinson, 1986; Avissar and Verstraete, 1990). The integration of these models in time yields predictions of the values of the main physical variables, thereby allowing the study of likely changes and their impact on environmental and human systems.

Atmospheric scientists are primarily concerned with the net flux of energy from the surface to the atmosphere, and its dependency on the condition of solar illumination. They have therefore developed a number of models and approaches (such as the two-stream approximation), which focus on describing the transfer of energy along the vertical, without too much concern or interest for the directionality of the reflected radiation. However, it is becoming increasingly evident that if we want to be able to predict the impact of climatic changes on the biosphere, and the effect of changes in the biosphere on the global climate, it will be necessary to understand the dynamic interaction between the atmosphere and the underlying surface. In particular, it will be important to identify the primary physical parameters that control the albedo of the surface. Clearly, it is not enough to accumulate data bases of albedo measurements, since that would not provide any useful insights on the likely evolution of this crucial climatic variable: It is necessary to develop physical models that describe how the nature, structure, and composition of the surface control its albedo, so that changes in these surface properties can be used to estimate changes in albedo.

Although the amount of solar radiation absorbed at the surface is difficult to measure continuously and at all locations, it is relatively easy to monitor the radiation reflected by the planet from artificial satellites. These measurements, made at the "top of the atmosphere," of course, include a variety of contaminating effects due to the absorption and scattering of radiation along its double path through the atmosphere. These atmospheric perturbations from gases, particulates, and clouds are very complex and have been treated elsewhere (e.g., Tanré et al., 1986). The interpretation of satellite remote sensing data also requires adequate solutions to a host of technical problems relative to the navigation and stability of the satellite platform, the calibration of the measuring instruments, etc.

As indicated above, natural surfaces are very anisotropic, that is, they reflect different proportions of the incident light in different directions: Single measurements of reflectance are not usually representative of the actual albedo of the surface (Deering, 1988). Since the latter is the ratio of the total reflected flux of radiation in all directions, divided by the total incident flux, it can be computed by integrating the bidirectional reflectance over the entire upward hemisphere. This, in principle, requires the observation of the same surface under a variety of viewing angles, an objective technically difficult to achieve. The development of physically based models of bidirectional reflectance may be very useful, since these models can be used to retrieve, with an inversion procedure, the fundamental physical parameters of the scatterers. It is then possible to estimate, analytically or numerically, both the anisotropy of the surface and its albedo.

Documenting the State of the Surface

Independently from these requirements specific to climate modeling activities, there is a definite interest in describing the state and evolution of the surface, from a physical, chemical, or biological point of view. Applications involving environmental monitoring, agricultural production, land use changes, etc., require a quantitative description of the parameters and processes that control the surface. Satellite platforms offer unique opportunities in this area, because of their ability to observe repetitively all regions of the globe, at high spatial resolution and with a consistent accuracy. The multispectral instruments mounted on many satellites take advantage of the spectral characteristics of the various natural and man-made surfaces, allowing their identification and classification.

Here again, the measurements are bidirectional, but the objective is not so much to integrate measurements as to understand the processes that control the radiation reaching the satellites. If we understood perfectly the state of the surface, we could, with the help of direct models, describe the radiation that is reflected at the surface and reaches the satellite instruments. In practice, however, we measure the reflected radiation at the top of the atmosphere, and we would like to retrieve the values of the relevant parameters at the surface. This is known as an inverse problem. The issue is therefore to extract the maximum amount of information about the surface from the spectral and angular distributions, intensity and polarization of the measured radiation at the level of the satellite.

Towards a Unified Modeling Approach

Remote sensing data are often promoted as the single universal solution to both the initialization and validation of climate models, as well as the ultimate tool to describe the state and evolution of most terrestrial biomes. The current interest in the further interaction between climatic change and environmental degradation enhances the role of satellite platforms as one of the significant tools of research for the next century; it is therefore important to establish scientific and technical connections between the climatic and environmental communities. Furthermore, since these scientific communities plan to use the same observing tool, it would be appropriate to propose the use of a single common model to study the interaction of the radiation field with the surface. Such a model should be capable of describing the albedo and the reflectance of the surface, and permit the retrieval of information on the fundamental physical parameters of the scattering elements.

This point of view offers new scientific opportunities. If the problem facing climatologists is cast simply as prescribing the surface albedo as a lower boundary condition for the integration of a numerical model, then the spatial and temporal distributions of the albedo, as provided by a large data bank, would suffice. A more essential challenge, however, is to validate these climate models, and this goal can be reached by comparing the directional radiances predicted by the model at the top of the atmosphere to the measurements of satellites (such as those used for ERBE). This approach, in turn, requires the accurate description of the bidirectional reflectance at the surface, because of its strong anisotropy. Finally, to the extent that the biosphere is a major factor in the evolution of the climate system (at a variety of space and time scales), it is important to describe the biosphere with tools that are compatible and can be integrated in common models.

It is therefore tempting to design and implement a common radiation transfer model to describe the interaction of the radiation with the surface. Such a universal model, to be used both for climate applications and for studying the dynamics of surface ecosystems, must verify a number of constraints: 1) it must be physically based, as opposed to being a statistical fit, since it must be usable for understanding the processes that affect the reflectance of the surface, 2) it must be reasonably simple in order to limit the computational burden on climate models, and on the processing of very large amounts of satellite data, and 3) it must be invertible, that is, there must exist an objective procedure to retrieve the values of the relevant physical parameters from actual satellite measurements.

This latter constraint requires additional discussion, to show that the capability to invert data sets with this universal model is relevant even for the limited purpose of albedo estimation. As indicated above, measuring the reflectance of each terrestrial surface from a large number of directions (viewing angles), and then computing the albedo through a numerical integration, is not technically or economically feasible. If an analytical representation of the albedo of a surface is available and if the relevant parameters in that formula are the same as those that can be retrieved from a suitable inversion of satellite data, then the albedo can be computed directly. On the other hand, if the albedo has to be computed numerically by integrating bidirectional reflectances and if only a very limited number of observations are available, then it is necessary to improve the estimation of this albedo by generating the bidirectional reflectances in many additional directions. In either case, the inversion step is required.

The constraint on invertibility implies a limit on the number of physical parameters that should be included in such a model. Clearly, a model used only in direct mode, that is, to generate reflectance values for a known surface, can have an arbitrary number of parameters. However, only a limited number of parameters can reasonably be expected to be retrieved with any amount of certainty or accuracy from an inversion procedure, and the number of independent physical parameters in a model should not exceed this "number of degrees of freedom" in the data set. Clearly, this optimal number of parameters depends on the analytical form of the equation, on the efficiency of the inversion procedure, and on the variability of the data. This complex but important issue is discussed in more detail below.

STRATEGY TO VALIDATE BIDIRECTIONAL REFLECTANCE MODELS

Any mathematical function with enough parameters can be forced to fit a particular data set. In this sense, the bidirectional reflectance data for an arbitrary surface can be fitted by an arbitrary polynomial of sufficient degree. The physical significance of the coefficients of this polynomial or the applicability of this formula to other situations may be very limited, however. In this section, we develop an argument to show that the validation of models of bidirectional reflectance requires the development of physically based models, that is, models whose fundamental parameters are well-understood, measurable physical variables, and also requires the inversion of such a model against actual data sets of reflectance data, followed by a comparison of the estimated values of the model parameters with independently measured values of these parameters. We start by briefly reviewing the kinds of models that have been proposed in the literature.

Overview of Bidirectional Reflectance Models

Following the work of Goel (1987), bidirectional reflectance models can be classified in five categories. Empirical models result from statistical fits to observations. These models allow the representation of the general dependency of the reflectance with respect to the angles of illumination and observation, without the need to take the details of the physical processes into account. Their range of validity is limited to those data used to derive the model, they cannot be applied to new or changing situations, and they do not permit the retrieval of fundamental physical parameters (e.g., Walthall et al., 1985; Pinty and Ramond, 1986).

Geometrical models describe the bidirectional reflectance on the basis of classical optics, they represent particularly well the illumination, and therefore the shadowing of scattering elements of finite dimension by direct solar radiation, and thereby include some description of the internal structure of the canopy. These models often represent the scatterers as geometrical volumes (cones, cylinders, spheres, or cubes) whose optical properties are more representative of the bulk properties of the canopy than of individual scatterers (e.g., Otterman, 1983; Li and Strahler, 1986; Norman, 1984).

The classical theory of radiation transfer in turbid media has been applied to plane-parallel media that display a natural arrangement of layers, such as soils and vegetation (e.g., Suits, 1972; Ross, 1981; Camillo, 1987; Myneni et al., 1987; Simmer and Gerstl, 1985; Dickinson et al., 1990). Kubelka-Munk applied the same theory to the transfer of radiation inside the leaf itself. These models are well suited to describe radiation transfer in homogeneous media where the interparticle distance is large enough and the media density low enough to satisfy the far field approximation. In such cases, the attenuation of the radiation intensity follows an exponential decay law. However, the occurrence of mutual shadowing, as observed at visible wavelengths over vegetation canopies, clearly shows that the far field approximation is not verified. As a consequence, turbid models cannot *a priori* represent special phenomena such as the hot spot, which results explicitly from the mutual shadowing of scatterers of finite size. This weakness in the representation of angular behavior is compensated by their correct description of the radiation balance inside the medium.

Hybrid models combine the approach of radiation transfer in turbid medium with the geometrical description of either the macrostructure of the canopy (e.g., Goel and Grier, 1987; Norman, 1984), or the mutual shadowing of oriented scatterers of finite dimension (e.g., Hapke, 1981; Nilson and Kuusk, 1989; Verstraete et al., 1990; Pinty et al., 1990). In the first case, the models are often two- or three-dimensional, and they may include a large number of parameters to represent canopies such as agricultural crops, with their row alignment and other characteristics. In the second case, the models are one-dimensional, and they emphasize the representation of the effects due to the orientation of the scatterers and the structure of the canopy. These models allow a physical description of the backscattering of radiation, and in particular of the hot spot phenomenon as it relates to the structure of the canopy.

Finally, recent computer models describe explicitly the transfer of photons in canopies. Monte Carlo, ray-tracing, graphical, and radiosity models attempt to represent as precisely as possible the transport of photons in a medium of arbitrary complexity, and use the latest computing and visualization techniques. Such models allow the most detailed and realistic representation of actual surfaces. They can serve as benchmarks for other models, and can therefore produce reflectance data for surfaces whose complexity is intermediate between what can be represented in all other models and actual surfaces in the natural world. In a sense, these models represent the ultimate laboratory for radiation transfer, where all elements can be controlled (Kimes and Kirchner, 1982; Ross and Marshak, 1984; Gerstl et al., 1986; Borel et al., 1991).

The Validation of Reflectance Models

The users of all these models can be grouped in two broad classes: those who are interested in the transfer of radiation per se and those who want to apply the models to practical remote sensing problems. The requirements of each group only partly overlap: In the first case, the complexity of the models is not a primary issue, if more complex models can bring about more realism. In the second case, the ultimate objective includes the possibility to invert the model against actual data sets in order to extract useful information about the state or evolution of the surface from these data. In this case, the models must be kept relatively simple with regard to the number of parameters.

The diversity of models described above reflects not only the scientific objectives of the designers, but also the intrinsic complexities of the medium under study. However, even in the case of one-dimensional situations, these models have not been thoroughly compared. It would be instructive to apply all models to the same extensively documented natural surface, but that would not per se guarantee that the physics included in the models was good enough. This is because the shape of the curves to fit is not extremely complex, so that most models with enough parameters would be able to adjust the values of the parameters to fit the data in some sense. Pinty and Verstraete (1991) considered three related hybrid models and showed that even structural changes in the form of the equation did not impair the ability of the model to fit the observed data with essentially the same root mean square error. However, even with this same quality of fit, the actual values of the physical parameters, as retrieved from the inversion procedure, are significantly different between the models. This implies that detailed and accurate laboratory measurements on the optical properties of the scatterers and structural characteristics of the medium are needed at the same time as the bidirectional reflectances are taken, so that a true validation can take place and different models can be discriminated.

Figure 1 shows the general strategy for the validation of physically based bidirectional reflectance models. This strategy is mostly relevant to models applied in the context of remote sensing. Following the diagram in clockwise direction from the top right corner, the values of m significant properties of the surface are measured and provided as input to models of bidirectional reflectance. Used in direct mode, these models produce either bidirectional reflectances or the albedo of the surface, or both, for any particular geometry of illumination or observation. These theoretical values can then be compared to actual measurements of the bidirectional reflectance of these same surfaces, but, clearly, this is only a comparison. The closeness of the two data sets does not necessarily imply the capability of the model to represent the critical physical processes that control the transfer of radiation: The model may be right for the wrong reason.

A second part of the validation strategy therefore consists in inverting the model against reflectance data, in order to retrieve the numerical values of the physical parameters that condition the signal. In the case of synthetic data, the values of those parameters are known, since they were used to generate the data initially. For lab or field observation campaigns, the optical and structural properties of the surface under observation must be measured at the same time as the reflectance. The same applies in the case of airborne or spaceborne observations, except that additional data on

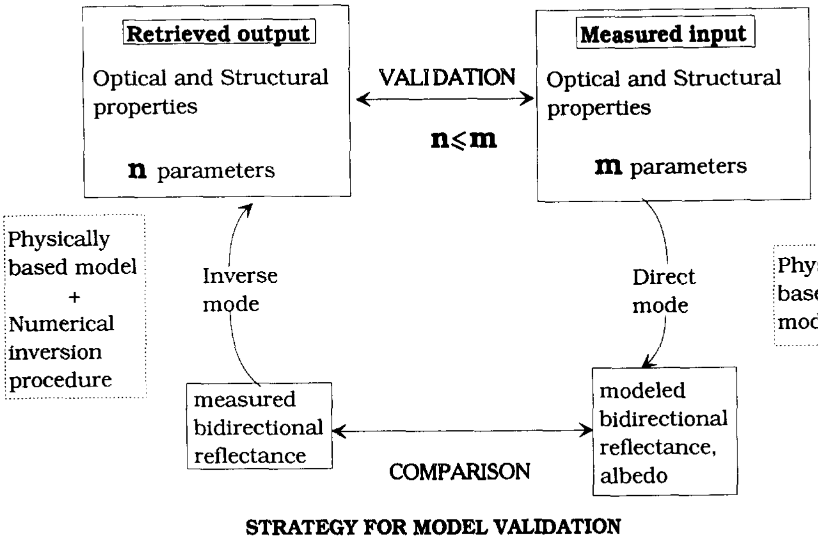

Figure 1. Diagram showing the strategy to validate bidirectional reflectance models by inverting them against observed reflectance data sets and comparing the values of the retrieved physical parameters to laboratory or field measurements of the same quantities (see text for details).

the state of the atmosphere are also needed to make appropriate atmospheric corrections.

This strategy requires access to an inversion procedure to retrieve the optimal values of the physical parameters that account for the observed variability of the signal, given the parametric form of the reflectance function. At the end of this step, one may very well find out that only $n \leq m$ parameters can be reliably retrieved, in the sense that the form of the model, the quality and efficiency of the numerical inversion scheme, the range of variability in the data, and the measurement inaccuracies do not allow more than n parameters to be estimated with any confidence. In the end, the comparison of the values of the retrieved parameters with actual measurements of the optical and structural properties of the canopy constitutes the validation of the model and of its inversion procedure.

Ideally, we would like to have $n = m$, whatever the value of m. In practice, noise in the data, inaccuracies in the numerical procedures of inversion, and limitations in the physical realism of the models combine to impose the more usual condition $n < m$. The challenge is therefore to find a compromise between the minimum number m of parameters needed to describe the scattering medium realistically, and the maximum number n of parameters that can actually be estimated from remote sensing.

It must be emphasized that this approach assumes remote sensing data to be the only source of information about the medium. It is clear that a mathematical model of the surface reflectance could also include any number of additional parameters on the nature, composition, structure, or evolution of the surface, if these values were provided independently from other sources of information.

Table 1 shows the minimum number of physical parameters that are reasonably needed to describe the bidirectional reflectance of the surfaces given in the first column. Clearly, even for surfaces that contain only two primary optical media, as is the case for sparse vegetation over bare ground, a minimum of 6–10 parameters are required. Whether these can actually be retrieved from an inversion will be discussed below in more detail.

REMAINING CHALLENGES FOR THE CURRENT BIDIRECTIONAL REFLECTANCE MODELS AND THEIR INVERSION

This section reviews the major challenges facing us in the modeling and inversion of bidirectional reflectance models, in the framework of their use in remote sensing applications. As seen in Figure 1 above, it is useful to distinguish between models used in direct mode only, and those that will be used in conjunction with an inversion procedure.

Modeling Challenges

All models of bidirectional reflectance represent the anisotropy of the surface as a function of the

Table 1. Number of Physical Parameters Needed to Model the Reflectance of a Surface of Given Complexity

Model Type	*Parameters*	*Minimum Number of Parameters*
[1] Homogeneous[a] semiinfinite[b] single medium	Optical properties (2) Structural[c] properties (2)	4
[2] Homogeneous finite single medium over a Lambertian surface	Same as [1] but with finite optical thickness τ (1) and soil albedo ρ_s (1)	6
[3] Heterogeneous semiinfinite dual medium (linearized[d])	Same as [1] but for 2 media, with fractional cover[e] σ added (1)	9
[4] Heterogeneous semiinfinite dual medium (nonlinearized)	Same as [3] but with macrostructure[f] distribution X (1 +)	10 +
[5] Heterogeneous finite dual medium (vegetation + soil)	Same as [1] but for 2 media, plus all four parameters above τ, ρ_s, σ, X	12 +

[a] Homogeneous refers to a horizontally uniform surface, heterogeneous refers to more than one optical medium in the horizontal.
[b] Semiinfinite refers to a deep and vertically uniform medium, finite indicates a medium of finite optical thickness.
[c] Structural properties include one parameter for the orientation distribution of the scatterers and one for the architecture of the canopy.
[d] Linearized refers to the fact that the reflectance is computed as a linear combination of the reflectances of each constituting medium type, weighted by the fractional covers of these media. Nonlinearized models include edge effects at the boundaries between different media.
[e] Fractional cover refers to the fraction of the surface occupied by the particular optical medium.
[f] Macrostructure distribution refers to the relative spatial arrangement of the various media, and may require more than one parameter for a realistic representation.

angles of illumination and viewing, and for specific values of physical parameters. In most cases, however, the contribution to the total reflectance that results from the multiple scattering of radiation inside the medium is treated quite separately from the single scattering contribution. Let R be the total bidirectional reflectance of the surface, R_s the single scattering contribution, and R_m the contribution of the second and higher orders of scattering:

$$R = R_s + R_m. \tag{1}$$

Although R_s is amenable to a rather exact solution, R_m is often conceived of as an approximation to the real case, because of the complexity of the mathematical problem (to treat the multiple scattering perfectly, one would have to follow all photons explicitly through the second and higher orders of interaction). In the case of vegetation, this distinction between the treatment for single and multiple scattering is appropriate because of the very different optical properties of leaves on both sides of the 0.7 μm threshold (Gates, 1980).

Some models derive a full equation for all orders of interaction, without making this distinction, and these are able to retrieve the single scattering contribution as a limit case when the single scattering albedo tends to zero (e.g., Myneni et al., 1987).

Single Scattering Contribution

One of the simplest ways to model the interaction between the radiation field and a complex medium like a soil surface or a plant canopy is to apply turbid medium concepts and classical radiation transfer theory. In this case, soils and plants are reduced to a cloud of scatterers, either soil particles or leaves. However, this implicitly assumes that the scatterers are small, numerous, and widely separated, in comparison to the wavelength of the radiation. This approach does not allow the explicit representation of mutual shadowing effects, but this effect can be taken into account using geometric optics. In other words, it is not possible, *a priori*, to describe the effects of the architecture of the medium (such as the hot spot phenomenon) with the classical theory of radiation transfer. Initial attempts to include an efficient description of the hot spot in such models lead to the addition of an arbitrary correction to the phase function in the radiative transfer equation to represent the backscattering effect (Hapke, 1981). More recently, Verstraete et al. (1990) and Pinty et al. (1990) showed that the description of the hot spot phenomenon automatically results from a better mathematical treatment, in which the total reflectance can be written as follows:

$$R = (R^{RT} - R_1^{RT}) + R_1^{GO} = R_m + R_1^{GO} \qquad (2)$$

where R^{RT} is the reflectance as given by the radiative transfer theory for all orders of scattering, R_1^{RT} is the contribution, in that same theory, due to single scattering only, and R_1^{GO} is the single scattering contribution derived from geometric optics. The first two terms on the right-hand side of the first equal sign represent the contribution to the bidirectional reflectance due to the second and higher orders of scattering. The retrieval of the structural parameters of the surface by interpreting remote sensing data therefore implies the use of hybrid models and geometric optics.

In general, the assumptions made in one dimensional vertical models are that the canopy is azimuthally symmetric (i.e., the orientation distribution of the scatterers does not exhibit a preferential orientation, such as is observable in crop fields or in heliotropic canopies) and that the density of the medium is constant vertically (i.e., the optical properties and the leaf area density do not vary with depth in the canopy).

According to van de Hulst (1964), a layer of isotropic scatterers (e.g., leaves) illuminated by isotropic downward radiation becomes optically deep (i.e., optically equivalent to a semiinfinite medium) when its optical thickness $\tau = (\kappa / \cos \theta_1)$ LAI exceeds $2(1-\omega)^{-1/2}$, where θ_1 is the solar zenith angle, κ is the average cosine of the angle between the normal to the leaves and the direction of illumination, LAI is the leaf area index of the canopy, and ω is the single scattering albedo of the leaves. When this is not the case, a canopy (or scattering medium) of finite depth must be considered, and another level of difficulty is reached. Typically, for vegetation, this condition is attained for an optical thickness of around 2–3 in the visible band and of 4–6 in the near-infrared. For visible radiation, and in the case of planophile canopies (i.e., when $\kappa / \cos \theta_1 = 1$), the leaf area index required to verify this condition is approximately equal to the optical thickness; in the case of uniformly distributed scatterers (i.e., when $\kappa / \cos \theta_1 = 0.5 / \cos \theta_1$), the leaf area index must reach values between about 4 and 6, depending on the cosine of the direction of illumination. For all canopies whose leaf area index is less than or equal to that limit value, this implies a rather small number of scatterers, especially when the leaves are large. In this case, the use of an exponential decrease to represent the transmission of radiation through the canopy may become inappropriate. In practice, many vegetation canopies are optically thick in the visible, but optically thin in the near-infrared region, where an optical depth greater than approximately 5 must be reached to guarantee a reflectance equivalent to that of a semiinfinite canopy. Therefore, models that assume deep canopies should be used with caution in the near-infrared spectral band, and new models that take explicit account of a finite leaf area index generated by a finite number of leaves with a specific size, location, and orientation must be developed.

Two- and three-dimensional models of bidirectional reflectance suffer from the same shortcomings as the one-dimensional models above. In this case, the remaining challenge is to account correctly for the edge effects between two or more media. Indeed, representing the reflectance of an inhomogeneous surface as a linear combination of contributions from the reflectances of the individual elements is equivalent to neglecting any possible nonlinear interaction between these elements, such as the shadowing of lower vegetation or soils by higher standing canopies. Qualitatively, for given illumination and observing conditions, the relative proportion of shadows is depending on the horizontal distance between the macrostructures that define the roughness of the surface elements, and their heights. This latter effect adds some significant nonlinear behaviour to the bidirectional reflectance, depending on the spatial distribution of the elements over the target; in other words the knowledge of the relative fractional coverage is not enough to solve the problem. The linear case is observed solely when the roughness of the media is negligible, or when the illumination and the observation is from the zenith. In both cases, there is no significant shadowing of one medium on the other.

Multiple Scattering Contribution

In principle, it would be necessary to follow each of the photon paths through their successive interactions with the canopy scatterers to describe correctly the second and higher orders of scattering for arbitrary orientations and optical properties of the scatterers. As indicated above, and even for simple canopies, this problem is untractable analytically: Camillo (1987) has explored this avenue and developed lengthy mathematical solutions, yet his treatment still assumed the underlying surface to be Lambertian and did not include the whole range of possible scatterer orientation distributions. Nilson and Kuusk (1989) used an approximate solution based on the Schwarzchild equation. Other authors have proposed performing the integration of the equation for multiple scattering numerically, by using iterative schemes (Myneni et al., 1987; Ganapol, 1989) or by solving the radiative transfer equation with a discrete ordinate method on non-Lambertian scatterers (Gerstl and Zardecki, 1985). In these derivations, the equation of Chandrasekhar is modified to take the orientation of the scatterers into account.

An intermediary approach has been proposed by Dickinson et al. (1990), following the suggestion of Hapke (1981). Starting from a two-stream representation of the radiative transfer equation for isotropic scatterers, Hapke (1981) had derived an approximate analytical representation of Chandrasekhar's $\mathcal{H}$ functions. This parameterization has been extended by Dickinson et al. (1990) to account for the orientation of the scatterers. In the limit case of a planophile canopy, this parameterization yields the exact solution obtained by Ganapol (1989). It has also been verified against the three-dimensional ray-tracing model of Kimes (1984) over a range of scatterer orientation distribution.

Despite such improvements, all these solutions remain valid only for scatterers characterized by an isotropic phase function. One way to extend the range of applicability of multiple scattering schemes is to introduce the similarity transformations suggested by van de Hulst and Grossman (1968). In the case of a uniform distribution of scatterer orientation, two media are considered similar if

$$\omega\tau(1-\Theta)=\omega'\tau'(1-\Theta'),$$
$$(1-\omega)\tau=(1-\omega')\tau', \tag{3}$$

where ω is the single scattering albedo, τ is the optical thickness of the layer, Θ is the asymmetry factor of the phase function, and the primed quantities refer to the second medium. If we select the second medium such that the scatterers are isotropic ($\Theta'=0$), an equivalent single scattering albedo can be defined obtained by combining the above two equations to yield

$$\omega'=\omega\frac{1-\Theta}{1-\omega\Theta}. \tag{4}$$

It can be seen that $\omega'=\omega$ when the asymmetry factor $\Theta=0$, $0\leqslant\omega'<\omega$ in forward scattering cases ($\Theta\rightarrow 1$), and $\omega<\omega'\leqslant 1$ in backward scattering cases ($\Theta\rightarrow -1$). If the terms $R_m=(R^{RT}-R_1^{RT})$ in Eq. (2) are evaluated using ω' rather than ω, the second and higher orders of scattering will be better estimated, since they will indirectly include the departure from isotropy of the scatterers. The order of magnitude of the effect can be readily estimated; if $\omega=0.8$ and $\Theta=0.2$, $\omega'=0.76$, and if $\Theta=-0.2$ with the same ω, $\omega'=0.83$. The effect of the anisotropy of the scatterers' phase function is therefore not negligible. It would be necessary to evaluate the performance of this correction against some of the other approaches and methods described above.

When attempting to model the effects of multiple scattering within finite and optically thin canopies, a realistic non-Lambertian soil surface must be considered because the downward scattered radiation that reaches the underlying soil could itself be significantly anisotropic. It has been shown above that the optical thickness of the canopy is directly linked to the leaf area index of this canopy. However, the radiation that exits from the plant cover and that is directly measured to produce the bidirectional reflectances must be at least slightly affected by the soil surface, in order to guarantee that the signal is sensitive to the total leaf area index. If this was not the case, that is, if the optical thickness in the near-infrared was greater than approximately 5.0, the radiation would be affected only by the top fraction of this canopy, and it would be impossible to retrieve the leaf area index from such measurements. The reflectance of the underlying soil must therefore be properly represented if one is to retrieve the optical thickness and the leaf area density of the canopy; this implies that models to be used to retrieve the leaf area index must include an appropriate representation of the bidirectional reflectance of the underlying soil.

In two- and three-dimensional models, the additional difficulty lies in accounting for the lateral interactions between the media inside the model. These interactions include the radiation that exits from one medium and acts as an additional source of radiation for the neighboring medium. In this case, the interaction of such a heterogeneous surface with the atmospheric diffuse radiation is made more complicated due to environmental contaminating effects.

Inversion Challenges

From the preceding discussion, it is clear that a lot of efforts have been devoted to the design and implementation of canopy models of varying complexity, to generate the bidirectional reflectance function of a given natural surface. The inversion of these models against actual data sets of bidirectional reflectances, however, represents the only way to extract useful quantitative information from remote sensing data, and constitutes the prime means to validate the models used in direct mode. The development of efficient and accurate inversion procedures is therefore crucial to both approaches.

The problem of the inversion is to retrieve the numerical values of the physical parameters that control the bidirectional reflectance, when a single equation in $m > 1$ variables is available to describe this reflectance, but multiple observations are available. The standard approach consists in varying the values of these parameters in some organized way until the difference between the theoretical reflectances predicted by the model, using for these parameter values and the actual reflectances is minimized in some sense (e.g., least mean square error). Such a procedure yields optimal parameter values, that is, values of the physical parameters that provide the best statistical fit with the data. Inadequacies of the underlying model, errors in the measurements, and inaccuracies in the inversion procedure are, of course, reflected in the values of these parameters, and particular care must be taken to ensure a minimum degree of confidence in the method.

One of the first attempts to invert a reflectance model on data was performed by Camillo (1987), who used a minimization algorithm from the International Mathematical and Statistical Library (IMSL). An analogous approach was applied by Pinty et al. (1989) to analyze data from bare soils and vegetation canopies with algorithms from the Numerical Algorithm Group (NAG) library. A few other attempts have been published using nonstandard libraries (Goel and Thompson, 1984; Nilson and Kuusk, 1989). Goel and Thompson (1984) have been using weighting factors different from unity to give more weight to some observations than to others. This procedure allows one to take partially into account the reliability of the data and the accuracy of the model over some regions of the upward hemisphere.

In all cases, the inversion procedure is liable to be sensitive to the values of the first guess of the parameters; it may display numerical instabilities which prevent the finding of an absolute minimum, or may be confused by the presence of multiple local minima or the inability to specify the values of the parameters because a range of values would give essentially the same minimum. These issues have been discussed extensively by Pinty et al. (1989) and Pinty and Verstraete (1991). In practice, from our experience, it appears that it may be unreasonable to attempt to retrieve more than about five or six parameters from an inversion procedure using quasi-Newton algorithms of minimization. These conclusions are also intimately linked to the number and angular distribution of the data.

Clearly, more work is needed to define and evaluate numerical procedures that represent the state-of-the-art in numerical computing. Extensive tests should be performed on various techniques to document the qualities and deficiencies of various methods in terms of their reliability, computational efficiency, and accuracy. The availability of one (or more) superior inversion procedure would be a major asset since, as indicated in Table 1 above, even simple canopy models may require a dozen physical parameters to describe the bidirectional reflectance of heterogeneous surfaces. A challenge for the scientific community would therefore be to select, test, and document fully one or a few inversion procedures that meet these requirements and would be generally available.

Since we cannot currently retrieve all the desired parameters with the inversion procedures available today, we need to simplify the problem, and this must be done in concert with the definition of scientific priorities. Clearly, if the radiation balance at the surface is the major focus of interest, then specific features of the reflectance such as the hot spot or specular reflection are not of prime importance. Since their representation would require additional parameters, it is best, in such a case, to take all measurements away from the angular configurations in which these effects would be important, and to invert a model with fewer parameters. Conversely, if information is desired on the structure of the canopy, then observations near the hot spot should be acquired, and the corresponding parameters in the model should be included. Although such considerations may guide the design of new instruments, we also recognize that existing satellite data archives may not include measurements in these special regions, in which case models with less parameters can be used on an operational basis.

CONCLUSIONS

In this paper, we have shown that the proper estimation of surface albedo and the retrieval of surface characteristics both require the use of bidirectional reflectance models. We have further argued that the validation of these reflectance models implies the inversion of such models against data sets of reflectance observations, and the comparison of the values of the retrieved parameters to the independent measurements of these physical parameters in the field or in the laboratory. Finally, we have shown that significant challenges remain in the development of better models of bidirectional reflectance and in the evaluation and selection of reliable, accurate inversion procedures.

In both cases, there is an urgent need to acquire and publish data sets that could be used in these validation exercises. From the discussion above, it results that collections of bidirectional reflectances, however large and carefully acquired, are of little use in this context, unless they are accompanied by extensive observations of the nature, composition, and structure of the medium under study. Specifically, the reflectance of deep homogeneous vegetation canopies is, in first approximation, controlled by four physical parameters (Verstraete et al., 1990; Pinty et al., 1990): the single scattering albedo, the phase function, the leaf orientation parameter, and the structural parameter. At the very least, the values of these parameters must be measured at the same time and for the very same canopy as the reflectance measurements.

It is unfortunately the case that very few data sets meet this stringent criterion of being both carefully acquired and associated with a full description of the relevant optical and structural properties. This lack of suitably documented data sets has severely limited our ability to validate models of the bidirectional reflectance of natural surfaces. We hope that significant thought and resources, both human and material, will be devoted to this issue in the near future.

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